15.—A preliminary investigation of the Yilmia Meteorite

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Abstract.
The meteorite found at Yilmia Hill in Western Australia has been shown by optical and electron microprobe analysis to be an enstatite chondrite of type II (or class E6). It is characterised by relatively abundant sinoite and tridymite. Several criteria indicate a low value for the temperature of final equilibration although the phase assemblage is beginning to be affected by wealthering.

Introduction

Only sixteen meteorites of the enstatite chondrite type were reported by Mason (1966). They were subdivided by Keil (1968) into two types (I and II) with two intermediate stones, on the basis of the iron content and other mineralogical characteristics which will be further noted below. A new find was made on Australian Selection (Pty) Limited ground at Yilmia Hill near Spargoville, W.A., late in 1969 by Mr. G. Coulson, but was unrecognised until June 1971. At this time a second occurrence was discovered only about 400m south of the first. The two occurrences were designated Yilmia I and Yilmia II.

It was not possible for the present authors to carry out the extensive statistical work required for a complete analysis of the meteorite. However, sufficient mineralogical and electron microprobe data have been accumulated to place it unequivocally into Type II of the enstatite chondrites and to point out some of its peculiarities. A limited point count on a representative field of view showed that the percentage of metallic nickel-iron was above average, and of silicates below average, for this type of meteorite. The class symbol according to the Prior-Mason system as modified by Keil (1969) would be Ce_2, while the Van Schmus and Wood (1967) group would be E6. The analytical data presented in the section on mineralogy are only given as approximate figures, since in view of the variability of the phases, individual analyses are almost meaningless.

Description of the find

Both masses occurred on flat, soft, lateritic soil which is underlain at a depth of about 30 cm with a hard laterite. The absence of outcrop in this area accounts for the ease with which the meteorites were found. The two masses were discovered three km north north-east of Yilmia Hill Trig Station at latitude 31° 12′ and longitude 121° 31′ (Figure 1).

The meteorites were partially exposed with the lower portions buried about 8 cm deep. A scatter pattern of smaller fragments (Figure 2A), perhaps thrown off on impact, northwards of the Yilmia I mass, together with the fact that the two impact sites lie on a north-south line, suggests that the meteorites came in on a south-north trajectory. Unfortunately the Yilmia II site was disturbed before the position of the loose fragments relative to the main mass could be recorded.

The scatter patterns represent something of a mystery, for this type of meteorite should have sufficient metal to resist fragmentation on impact, especially in soft soil. The alternative suggestion that fragmentation is the result of weathering does not explain the scatter over a distance of one metre or the relatively unweathered state of the exposed surfaces.

Although the lateritic area surrounding the sites was searched carefully, no further discoveries were made.

The main mass of Yilmia II (figure 2 B and C) is the best preserved and roughly arrow shaped, the blunt point being originally directed towards the north. The side that faced south is almost flat. The buried fragments of Yilmia I, when pieced together, indicate a roughly similar shape.

The buried portions were severely weathered to a rusty yellow brown colour. The weathered lower side of Yilmia II is strongly exfoliated or layered, unlike the exposed upper half which is apparently devoid of layering. The exposed surfaces are dark brown, fairly smooth and undulose. Irregular and pentagonal crack patterns were seen on some of the more weathered surfaces. Freshly cut surfaces had a bluish colour which became oxidised upon exposure within a matter of days.

Yilmia I weighed 16.2 kg of which the main mass weighed 8.6 kg. Yilmia II weighed 23.8 kg, the weight of the main mass being 11.3 kg. The greater part of these finds are preserved as samples 13192 and 13197 respectively at the Western Australian Museum. Almost 100 gm at the Kalgoorlie School of Mines have sample numbers 10951.1 and 10951.2. Small samples exist at CSIRO Laboratories, Perth, and in the Geology Department, University of Melbourne.

All the mineralogical data in this paper refer to the find Yilmia I (see Figure 2A). Analyses were carried out on an MAC-400S microprobe analyser operating at 20 kV for all elements except carbon, nitrogen and oxygen, which were analysed at 8 kV. For the most part metallic standards were used, although comparison was made with other oxides, sulphides and silicates. Apatite was used as a phosphorus standard.

Mineralogy

From the mineral assemblage shown in Table 1, and the detailed composition of the phases,

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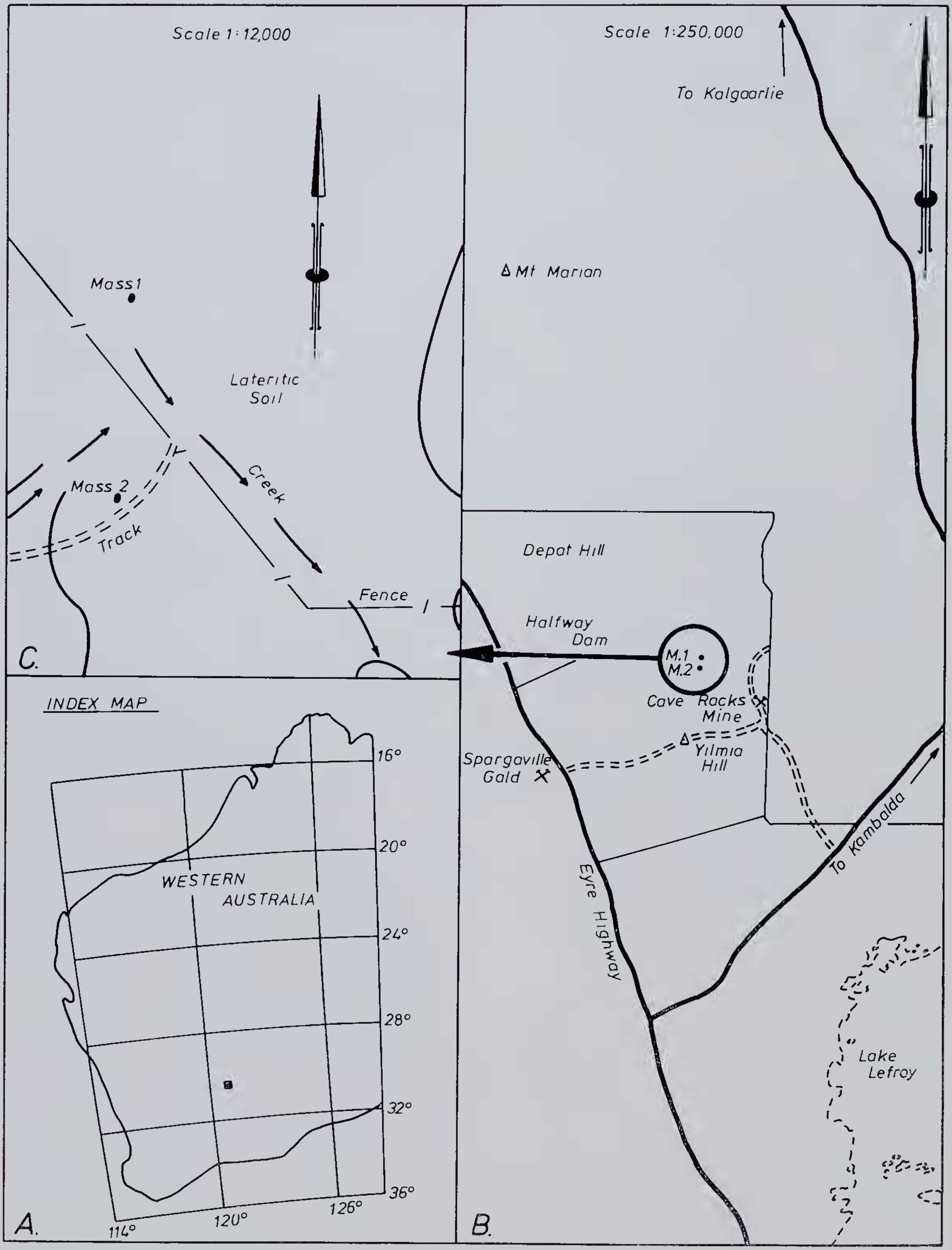

Figure 1.—Location map for the Yilmia Hill meteorite discovered about 10 km West of Kambalda.

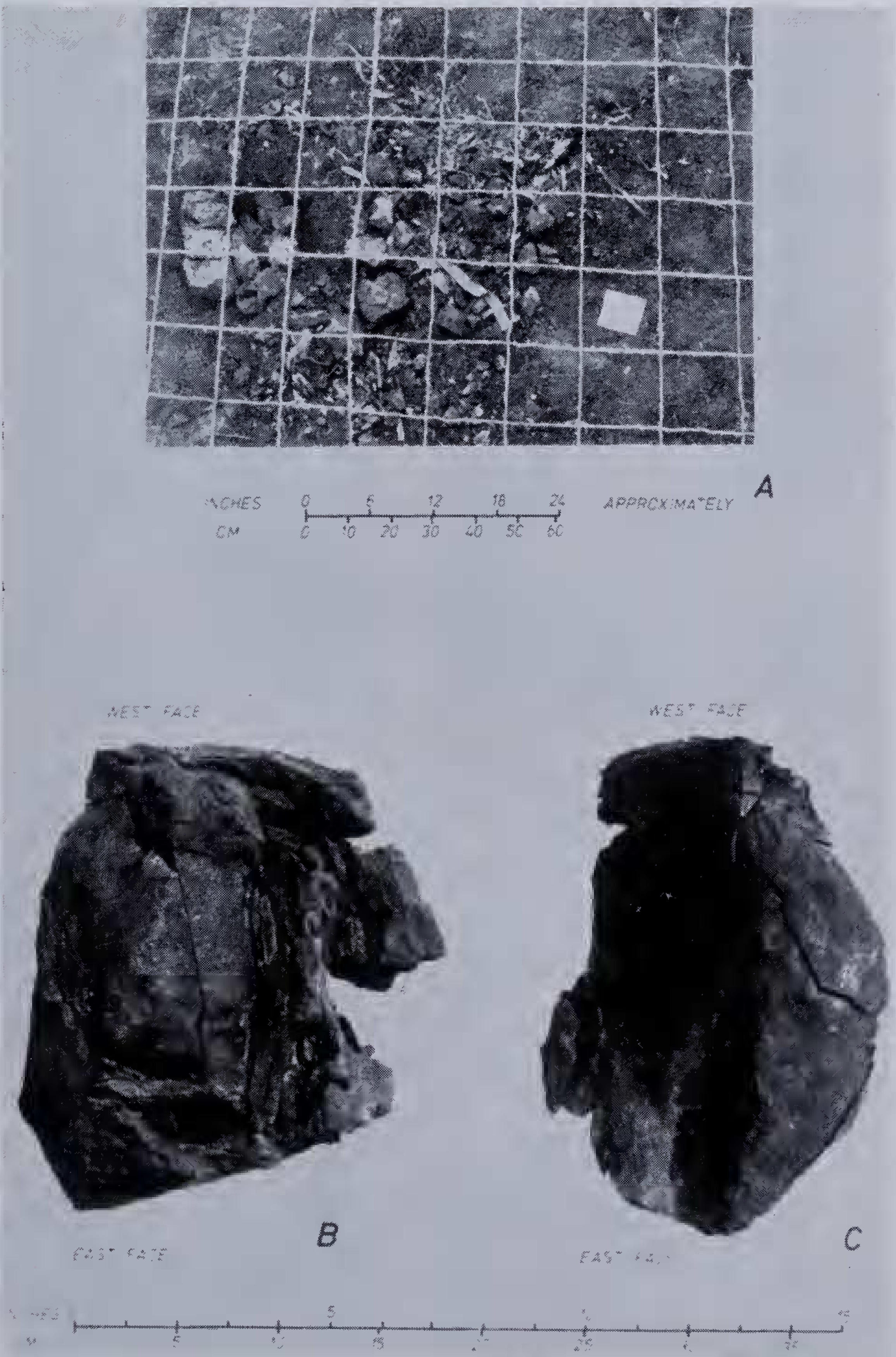

Figure 2.—(a) Scatter pattern of mass Yilmia I, north being to the right of the photograph. The white card marks the spot from which came the portion of the meteorite described in this paper. It is possible that this portion was moved to this spot after discovery of the site.

(b) Main mass of Yilmia II, showing smooth surfaces exposed to the air, and the layered buried portion. The pointed (northern) side is towards the viewer.

(c) Yilmia II viewed obliquely from above relative to position as found. The right hand side was facing north.

Table 1

Phases Present in the Yilmia Hill Meteorite

Opaque Phases :

Phase	Ideal Composition	Minor Elements Present (Approximate %)
native iron*	α Fe	2·4 Ni, 0·4 Co, 0·2 Cr, 0·1 Ti
kamacite	α Fe ($<$ 7·5% Ni)	5–7½ Ni, ∼1 Si, 0·3–0·6 Co, ∼0·1 Zn
taenite	γ Fe (8–55% Ni)	12–16 Ni, ∼1 Si, 0·4 Co
troilite	FeS	1–1½ Cr, ½–1 Ti, 0·1 Mn, 0·1 V, ∼0·1 Zn, ·05 Co
alabandite	MnS	Up to 21 Fe, 2 Mg, 0·1 Cr, $<$0·5 Ca, ∼0·1 Zn
daubréelite	$FeCr_2S_4$	3 Mn, ∼·15 Zn
oldhamite	CaS	2 Fe, 0·6 Mn, 0·3 Si
schreibersite	Fe_3P	23–26 Ni, 0·15 Co, some S, ∼·05 Zn
pentlandite*	$(Fe, Ni)_9S_8$	Co
graphite	α-C	

* May be an alteration product.

Transparent Phases:

Phase	Ideal Composition
enstatite	$MgSiO_3$
oligoclase	$(Na, Ca)(Al, Si)_4O_8$
tridymite	SiO_2
sinoite	Si_2N_2O
clinopyroxene	$(Fe, Mg, Ca)SiO_3$

the meteorite is a Type II enstatite chondrite. In thin section some relict chondrules can be distinguished. A feature of the sections is the segregation into metal-rich and sulphide-rich regions (Figure 3 A and B) and into oligoclase-rich and estatite-rich regions, on a scale of a few mm. Although the sections studied were fairly fresh, and most of the phases were unaltered, much of the oldhamite had been weathed away, and no good section of this mineral was exposed. In some areas, kamacite and alabandite were partly altered to an oxide phase (Figure 3C). Even where the original phase was kamacite, sulphur was present in the product. Some of this has undoubtedly been introduced in the weathering solutions, but there also seems to be a thin rim (∼ 1μm) of sulphide surrounding many kamacite grains, and in some cases this is left unaltered by the mild weathering, showing the outline of the original grain. One weathered grain was apparently after schreibersite. Analysis of these regions is not possible on a quantitative basis, because they are heterogeneous on a micron scale. However, many microprobe traverses show the presence of nickel-rich regions in which Ni may exceed iron by as much as five to one, and the total metal counts may exceed those from a monoxide. Sulphur is sometimes present, and the example shown in Figure 4 could be interpreted as a very small grain of pentlandite, containing some enrichment of cobalt. These phases are evidently not in equilibrium.

Siliceous Minerals

Enstatite—This phase is an enstatite of low manganese content. Its iron and calcium contents are as expected for Type II, but its aluminium content is lower than usual. Full quantitative data were not obtained. *Oligoclase* and *tridymite* are also present; probe data were obtained only for identification purposes, so no minor element trends can be quoted. The SiO_2 phase was not obvious in our thin section, and a few grains were removed from the polished section for Debye-Scherrer analysis. It was clearly identified as tridymite and was quite abundant. *Sinoite,* Si_2N_2O occurred in several large grains in the polished section. It forms hard, columnar crystals, which normally fluoresce strongly under electron bombardment. Some areas, however, fluoresced only weakly, and it is evidently dangerous to take the fluorescence as the major diagnostic criterion for this mineral.

Opaque minerals

Kamacite is, as usual, the most abundant opaque phase. It contains 5-7½% nickel, 0.3-0.6% cobalt, and up to 1% silicon. Apart from the even lower silicon content, these figures are typical of kamacite from Type II enstatite chondrites, although some zinc (up to 0.1%) also seems to be present in the Yilmia material. One grain of native *iron* was observed adjacent to troilite and the more typical kamacite; when carbon coated, its colour was distinctly different from that of the latter. This contained only 2.4% nickel and no silicon. The minor elements present included 0.4% Co, 0.2% Cr, and 0.1% Ti, figures which suggest that it may have been formed by weathering from the adjacent troilite, since the phase assemblage is still highly reducing. Ni and Co would need to be contributed from kamacite and taenite.

Graphite is generally associated with the kamacite.

Taenite occurs in several grains, usually adjacent to kamacite, and was recognised by its high nickel content. This is then the third enstatite chondrite to contain taenite, and the second of Type II. The nickel content of 12-16%

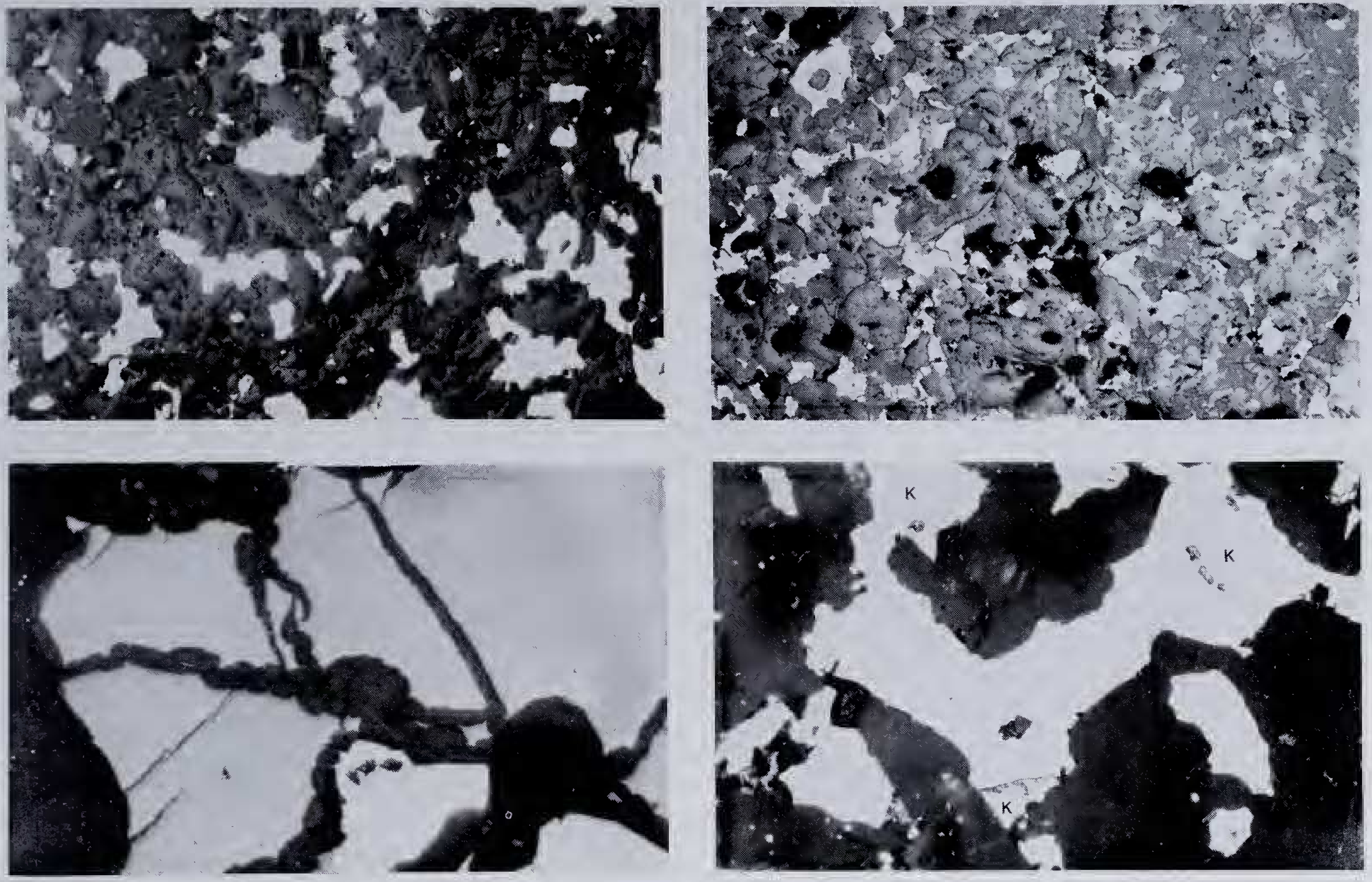

Figure 3.—Micrographs of the Yilmia I Meteorite. (a, top left) A metal rich region. The light phases are taenite and kamacite. Only two grains of sulphides are visible in this field. Width of field 2.2 mm.

(b, top right) A sulphide rich region. The light areas are mainly troilite, alabandite, and daubréelite, with some schreibersite and a few metallic grains at the right hand edge. Oldhamite is present in some of the dark pits. Width of field 2.2 mm.

(c, lower left) Alabandite altering along cracks to an oxide phase. The white area is troilite. Width of field 140μ.

(d) Large schreibersite complex (white areas). Width of field 560μ. Kamacite grains marked K.

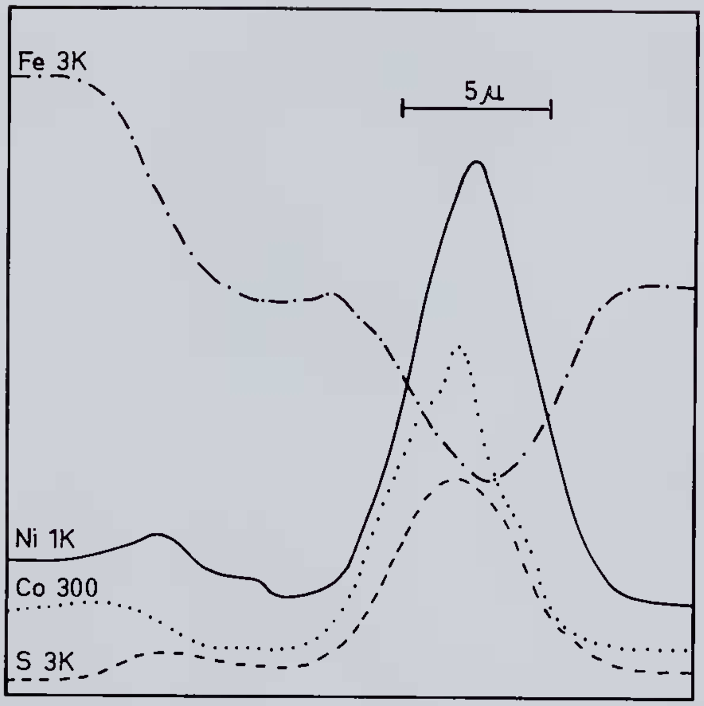

Figure 4.—Traverse across weathered region using the electron microprobe. The sulphide grain is apparently pentlandite containing some cobalt. It is not possible to say whether the pentlandite is an original meteorite phase, or a product of weathering. The symbol identifying each trace indicates the element and the full vertical scale in counts per second.

is considerably higher than that in Adhi-kot and Hvittis. Its cobalt and silicon contents (~ 0.4% Co and up to 1.1% Si) are similar to those of kamacite. The high nickel content may correspond to a lower temperature of formation of the Yilmia meteorite, since the two-phase region between kamacite and taenite increases considerably as the temperature is reduced.

The *troilite* seems typical of the Type II enstatite chondrites, containing 1-1$\frac{1}{2}$% chromium, $\frac{1}{2}$-1% titanium, ~ 0.1% manganese and zinc, up to 0.1% vanadium, about 0.05% chromium, and sometimes traces of nickel, copper and silicon. As usual, troilite is finely intergrown with daubréelite; where small areas are isolated in the latter, titanium values may be anomalously high.

Oldhamite was present, but as it did not polish well (see above), its composition could not be determined categorically. In addition to calcium and sulphur, the following elements were measured: Fe to 2%, Mn to 0.6%, Si to 0.3%, and traces of Mg, Cu, Ni and Co. It is likely that these will be maximum figures (errors being due to the presence of accessory minerals and weathering products), so this oldhamite is unusually low in manganese, and probably also in magnesium.

Mangonoan daubréelite is close to the ideal composition $FeCr_2S_4$, with somewhat less than 3% manganese replacing iron. There are sometimes trace amounts of Si and Ti. Zinc is usually about 0.1 to 0.2%, although in a few grains the amount may reach 0.5%. The polishing relief between troilite and daubréelite makes it difficult to analyse narrow lamellae of the latter; they often give spuriously high iron counts.

Ferroan alabandite is quite variable in composition; as stated in Keil (1968) there is a tendency for calcium to increase and for sulphur and manganese to decrease as the iron content increases. One grain had a very low Mn/Fe ratio of 2.1/1. There was usually about 2% magnesium, 0.1% chromium, 0.1% zinc, and up to 0.45% calcium.

Schreibersite may occur as small grains in association with kamacite, or as large structures such as that shown in Figure 3D. The nickel content is high (~ 23-26%) in common with all other type II enstatite chondrites, and cobalt is low at about 0.15%. Silicon was not always present, but sulphur and zinc were consistently slightly above background.

Discussion

This work was done concurrently with that described by El Goresy and Lovering (1972), and by Buseck and Holdsworth (1972) at the 35th Annual Meeting of the Meteoritical Society. Both of these groups of workers used material from the main mass of Yilmia II. Our results are consistent with their abstracts, although we have been unable to find osbornite or the new zinc-containing sulphide mineral described by the last-named authors, in spite of careful search in the likely areas.

If the low manganese and magnesium counts in the oldhamite are real, the curves of Skinner and Luce (1971) would suggest a very low minimum temperature of formation (below 600°C), which agrees well with the value obtained from the calcium content of the alabandite, and the high nickel content of the taenite. Arguments of Larimer (1968) in the case of the Jajh deh Kot Lalu meteorite, which falls closest to Yilmia on Skinner and Luce's curves, also indicate a possibly low temperature of formation (720 ± 140°C) based on the activities of Si, Fe and $CaSiO_3$, which are unlikely to be very different in the two meteorites. The presence of tridymite indicates a much higher temperature at some stage in the meteorite's history.

Sufficient work has been reported here for classification purposes, and for a comparison of many properties with other enstatite chondrites. A full analytical coverage is still required, together with a comparison of the two masses, Yilmia I and II.

The meteorite phase assemblage is most similar to that observed in Jajh deh Kot Lalu, but the composition of the phases is different enough to make it unlikely that both falls were due to a single meteoritic event. Probably the most significant difference would be the higher free silica and sinoite, the low magnesium content of the alabandite and odhamite, and the presence of taenite in the Yilmia meteorite.

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